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DEVELOPMENT OF PERTURBATION PROCEDURES FOR NONLINEAR INVISCID A--ETC(U)
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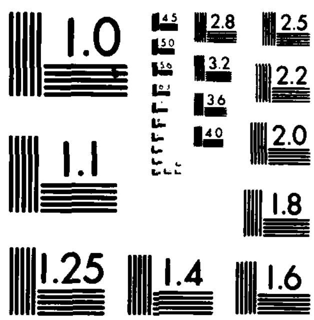

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 82-0391	2. GOVT ACCESSION NO. AD-A114 825	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF PERTURBATION PROCEDURES FOR NONLINEAR INVISCID AND VISCOUS FLOWS		5. TYPE OF REPORT & PERIOD COVERED ANNUAL 1 FEB 81 - 31 JAN 82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) DAVID NIXON		8. CONTRACT OR GRANT NUMBER(s) F49620-79-C-0054
9. PERFORMING ORGANIZATION NAME AND ADDRESS NIELSEN ENGINEERING & RESEARCH, INC 510 CLYDE AVENUE MOUNTAIN VIEW, CA 94043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2307/A1
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BOLLING AIR FORCE BASE, DC 20332		12. REPORT DATE FEBRUARY 1982
		13. NUMBER OF PAGES 7
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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MAY 25 1982
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TRANSONIC FLOW
NUMERICAL ANALYSIS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Certain topics on transonic flow theory and on numerical truncation errors have been investigated. In transonic flow theory the extension of the transonic perturbation method to include flows where shock waves vanish and the development of the technique to treat separated flows was undertaken with satisfactory results. Two other topics that were investigated concerned the application of perturbation theory to accelerate convergence of numerical solutions to predict potential flow. Finally, for transonic flow, the cont.

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development of a "potential-like" theory to more closely approximate the Euler equations was undertaken. A non-linear truncation error analysis was performed on certain Euler equation algorithms to develop corrections for the solution. An outcome of this work was the derivation of a criteria for use in adaptive mesh techniques.

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DEVELOPMENT OF PERTURBATION PROCEDURES FOR NONLINEAR INVISCID AND VISCOUS FLOWS

1. INTRODUCTION

The main objectives of the work on Air Force Contract F49620-79-C-0054 are concerned with transonic flow theory and certain aspects of numerical analysis. The topics of transonic flow are concerned primarily with developments of the transonic perturbation theory (ref. 1) and the numerical analysis topics are concerned with a nonlinear truncation error analysis.

The developments of the transonic perturbation theory that were investigated are as follows.

1. Test the ideas of the mathematical and physical perturbation theory to solutions of the Navier-Stokes equations, particularly for separated flow.

2. Investigate the feasibility of removing the restriction of no generation or loss of shock waves in a steady or unsteady perturbation.

3. Investigate the possibility of accelerating convergence of potential equation solutions by using the perturbation theory. Two approaches were studied, namely:

   a. a grid refinement technique using a sequence of three or more grids; and

   b. use the strained coordinate method in conjunction with the classic ideas of convergence acceleration.

In addition to the above noted objectives the following investigations, connected with transonic flow theory, but not necessarily with the transonic perturbation theory, were conducted:

4. Examine the possibility of modeling strong shocks in a potential formulation by using the concept of an internal energy to represent the effect of the vorticity transport.

5. Examine the possibility of using a single equation to accelerate the convergence of the Euler or Navier-Stokes solutions.

The research objectives in numerical analysis are:

6. Truncation Error Analysis

a. Derive the nonlinear truncation errors for the generalized Lax-Wendroff schemes and the implicit scheme of Beam and Warming for the two-dimensional Euler equations.

b. Implement the correction procedure to suitable existing, practical, codes based on the MacCormack scheme and the implicit scheme. Test for a parabolic arc airfoil in harmonic motion at transonic speeds.

2. STATUS OF RESEARCH EFFORT

The status of each of the research objectives is briefly described below. In order to identify each segment with its place in the research objectives the same notation is used.

1. Navier-Stokes Perturbations.- In the previous years of the above contract, a transonic perturbation theory was developed so that a selected number of solutions of the Navier-Stokes equations could be used to obtain estimates of the flow at other conditions. This earlier work concerned mainly attached flow and the present work is directed to attempting this method for separated flow. A study of the flow phenomena indicates that the theory can be used for shock induced separated flows and this has been confirmed by the application of the theory to experimental data. An example of application to this theory is given in Figure 1. The experimental data is from Stivers (ref. 2). A second part of this investigation is to determine whether the "mathematical" perturbation theory can be used to estimate the effects of viscosity for separated flow. A rationalization (ref. 3) of this theory has been developed and in principle separated flows can be treated. However, there

is a difficulty in computing an adequate base inviscid solution since in many cases the shock is at the trailing edge, whereas the separated flow shock is upstream of the trailing edge.

2. Perturbation Theory With Vanishing Shock Waves.- A major restriction of the present transonic perturbation theory is that shock waves cannot be generated or destroyed during the perturbation. A study of this problem showed that the interpolation theory can be used if three (rather than two) solutions are known. The additional result is necessary because the governing equation set changes at a critical flow. In the course of this investigation several points concerning transonic flows arose. The analysis, which is based on integral equation theory, rederived Morawetz's nonexistence proofs for shock free transonic flows and also suggested that numerical algorithms which are not nonlinear may not be mathematically correct. Results for examples when shock waves vanish have been obtained. In Figure 2 an example computed using two subcritical solutions and one supercritical solution is shown. Since fairly accurate subsonic solutions can be obtained (ref. 4) from an incompressible solution by the use of compressibility factors, a further simplification of the theory requires only the incompressible solution and one supercritical solution. An example is given in Figure 3.

3. Convergence Acceleration.- A consequence of the mathematical perturbation theory is that data from a coarse and a medium grid numerical solution can be used to estimate the starting solution for the fine grid. The investigation showed that considerable decreases in the computation time (75% decrease) can be obtained by this means but that this improvement only occurs under certain circumstances. However, the technique does not, in any of the cases computed, significantly increase the computational time.

An alternative investigation into convergence acceleration was to couple the basic ideas of the perturbation theory with the classic ideas of convergence acceleration. The basic premise of this idea is that slow convergence of the shock location is

the cause of the failure of the classic applications. A study of some computed results indicated that this hypothesis is incorrect and the investigation was terminated.

4. Strong Shock Potential Theory.- A strong shock potential theory was derived by adding the effect of entropy production to the isentropic gas law. This theory is approximate and assumes that grid lines in the near streamwise direction are aligned with streamlines. It is also assumed that the flow is at most weakly rotational. An example is given in Figure 4. It was also determined that a back-out formula does not exist. During the course of this study it was found that the conventional transonic potential theory is inconsistent since consistency requires that momentum is conserved through a shock wave. In transonic potential theory momentum is not conserved. A more consistent theory can be derived by including the momentum error in the analysis but it is physically unrealistic since the errors decrease entropy. It was also found that conventional transonic difference schemes do not conserve mass through the shock capture region although mass is conserved at the shock extremities.

5. Convergence Acceleration of Euler Equations.- The basic idea of this study is to determine if a single equation could be constructed so as to carry the numerical errors in an Euler solution to some extent, thus avoiding the need to iterate all five conservation equations at each step. It is concluded that the modified potential equation noted in the preceding section is adequate for this task.

6. Truncation Error Analysis.- The final task was to analyze the nonlinear truncation errors of two finite difference schemes for the two-dimensional unsteady Euler equations. The method of correcting for the leading truncation error was extended for the two-dimensional problem and was very successful for the explicit scheme. The correction procedure was found to be unstable for the implicit scheme and was not extended to two dimensions. The results of this task, along with some other

work, were presented at the 5th AIAA Computational Fluid Dynamics Conference held in Palo Alto, California, on 22-23 June 1981 (ref. 5).

3. TECHNICAL APPLICATIONS

The most recent application of the research developed under this contract was the simulation of aileron buzz on an experimental wing section designed by Gates-Learjet. The indicial response was generated by the Computational Fluid Dynamics Branch at NASA/Ames Research Center who solved the Reynolds averaged Navier-Stokes Equations. The aerodynamic response was directly coupled to a structural model of the aileron. The indicial method gives enormous savings in computer time since a single direct calculation takes about two hours on the ILLIAC IV computer.

Most of the research sponsored under the present contract is fundamental and the development of applications is proceeding under alternate sponsorship. Developments of this research have been sponsored by the following organizations:

NASA/Ames Research Center (Applied Computational Aerodynamics Branch)

NASA/Ames Research Center (Computational Fluid Dynamics Branch)

Naval Air Systems Command

Lockheed-Georgia Company

Office of Naval Research

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5. PERSONNEL

The Principal Investigator on the steady perturbation theory is Dr. David Nixon. For the numerical analysis aspects Dr. Goetz H. Klopfer is Co-Principal Investigator. Dr. G. David Kerlick is closely associated with the work.

5.1 Papers and Reports

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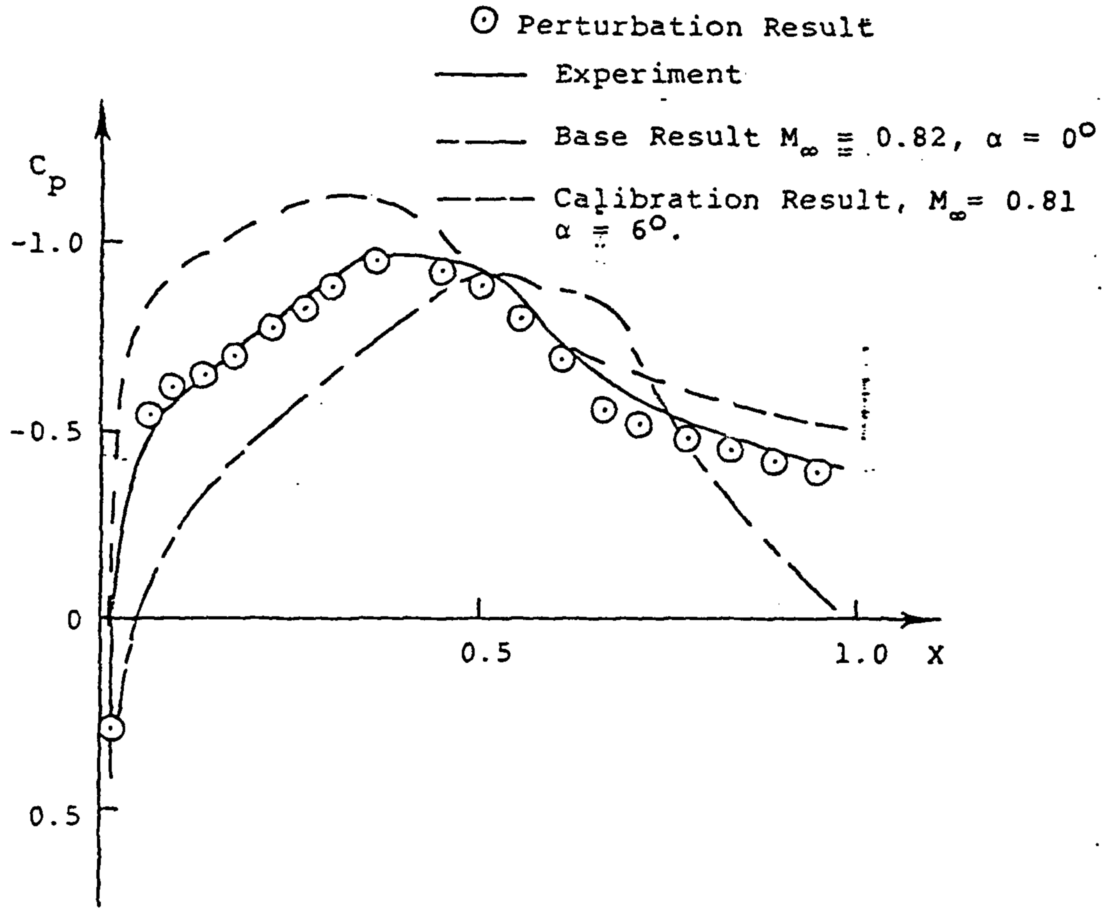

Figure 1.- Pressure distribution on the upper surface of a NACA 64A410 Airfoil; $M_\infty = 0.82$, $\alpha = 4^\circ$.

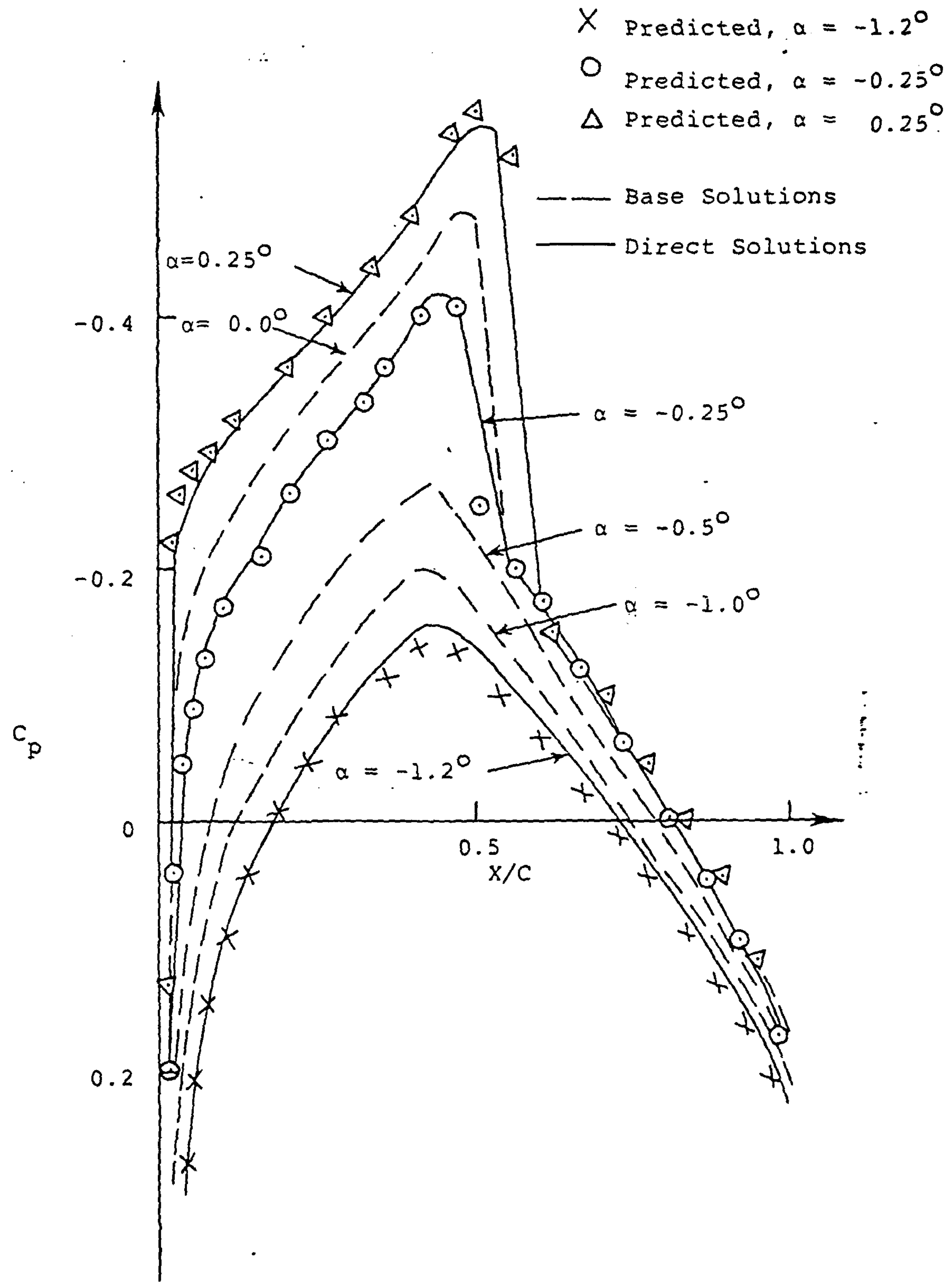

Figure 2.- Interpolation theory for the upper surface an NACA64A006 airfoil at $M_\infty = 0.85$

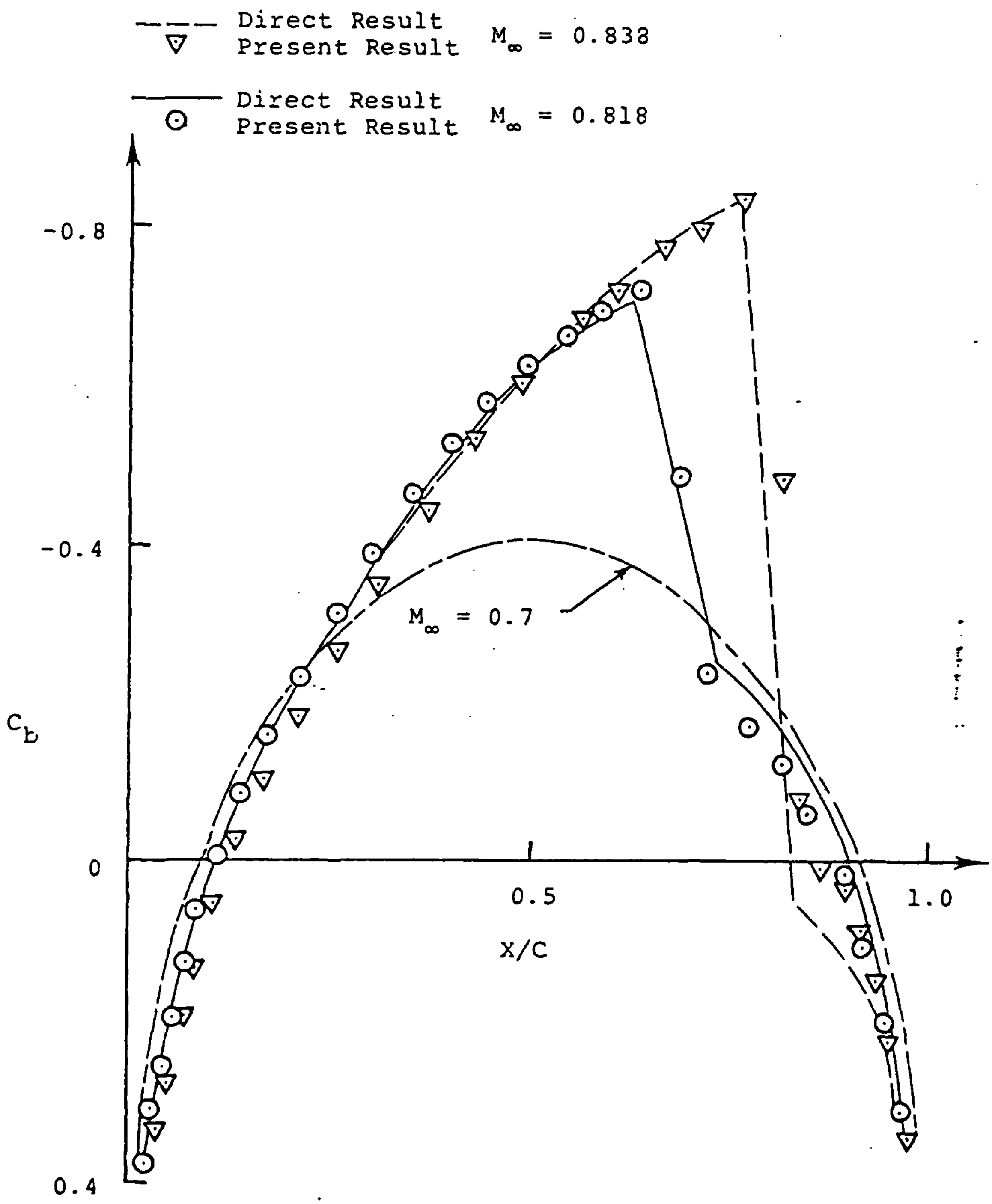

Figure 3.- Pressure distribution around a 10% Biconvex Airfoil.

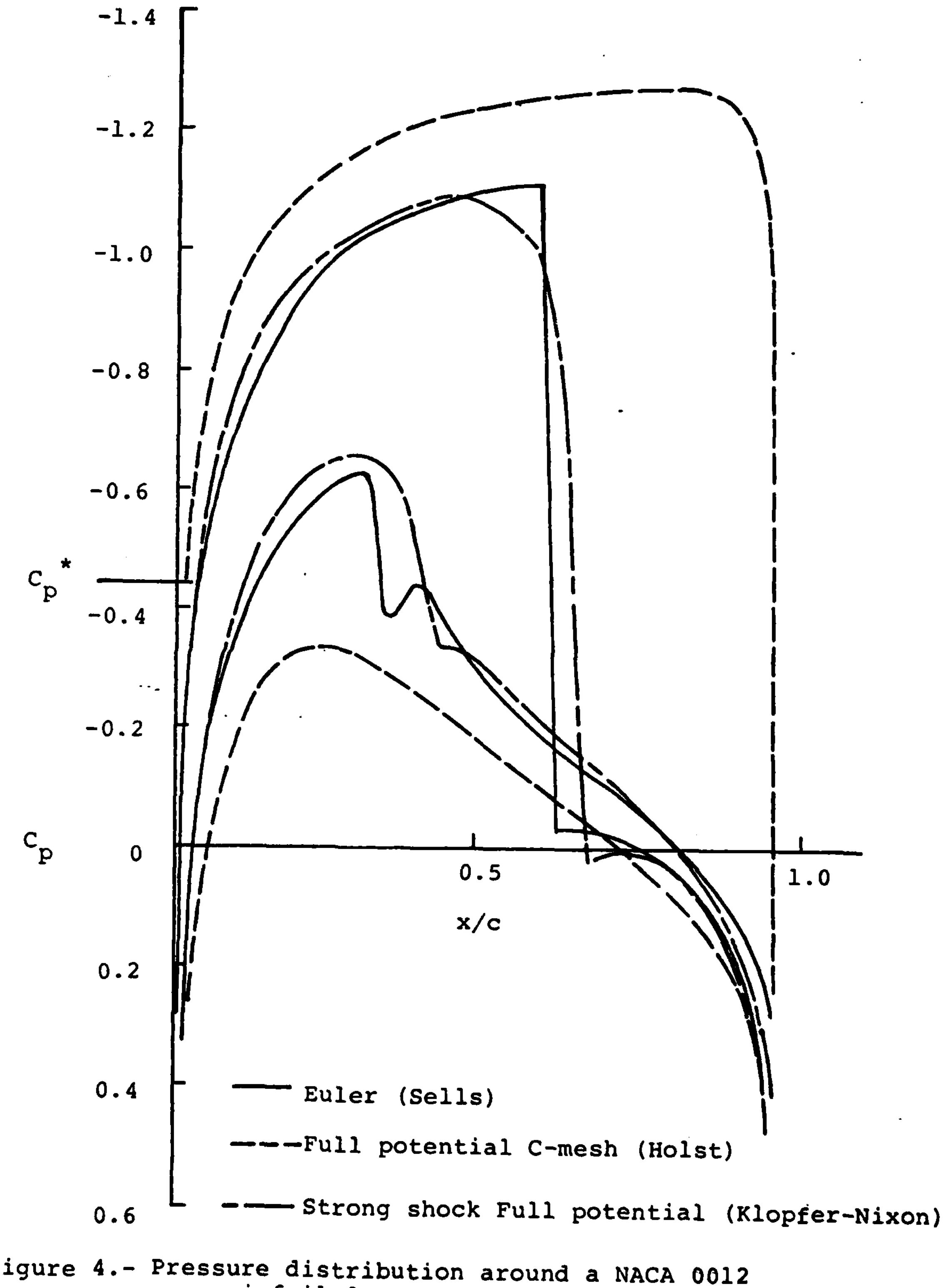

Figure 4.- Pressure distribution around a NACA 0012 airfoil @ M_∞ = 0.80, α = 1.25°.

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